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Technical Note

1975-49

W. E. Courtney

Printed-Circuit RF-Keyed
Crossed-Field Amplifier

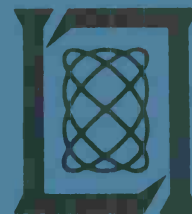
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FOR THE COMMANDER

A handwritten signature in dark ink, reading "Eugene C. Raabe". The signature is written in a cursive style with a large, stylized "E" and "R".

Eugene C. Raabe, Lt. Col., USAF

Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

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CROSSED-FIELD AMPLIFIER

W. E. COURTNEY
Group 33

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ABSTRACT

This report describes an experimental and theoretical study of an RF-keyed linear format Crossed-Field Amplifier, (CFA), using a printed-circuit slow-wave structure. The theoretical results indicate that higher interaction impedances than have presently been obtained with printed-circuit slow-wave structures will be required to achieve the goal of low RF-keying levels. Experimental results indicate good agreement between theory and experiment for the phase velocity of the slow-wave structure and reasonable agreement between theory and experiment for the CFA.

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I. Introduction

RF-keyed crossed-field amplifiers, (CFA's), have been constructed (Refs 1, 2 and 3) which require RF input power levels on the order of kilowatts. The present program was initiated to examine the feasibility of RF-keying a linear format CFA with input power levels in the 100 watt region while employing techniques, such as printed-circuit slow-wave structures, to achieve low-cost technology.

Although printed-circuit slow-wave structures have been successfully employed in injected beam CFA's and TWT's, they have not, as yet, been successfully integrated into an RF-keyed CFA.

II. Theoretical Studies

The performance of the linear format CFA was analyzed using the Dematron computer program, (Refs 2 and 4). Fig. 1 shows the CFA structure which consists of a slow-wave circuit, a secondary-emitting sole, a source of priming electrons, and crossed-electric and magnetic fields. The associated parameters are shown in Table I for a tube 19.0 cm long.

The anode-cathode voltage was specified as 10 kV. This was believed to be a reasonable voltage for a tube to be utilized at an element or subarray level. The parameters of the secondary-emitting sole utilized were those for the new sole materials which were available in this Laboratory. The crossover voltage which is the significant parameter for RF-keying is 25 volts compared to 150 volts for platinum.

Computations were made with interaction impedance, RF drive power, priming current, and circuit length as variable parameters. The interaction impedance is defined as

$$K = \frac{E_z^2}{2\beta^2 P} \quad (1)$$

where K is the interaction impedance for the n^{th} space harmonic

β is the phase constant for the n^{th} space harmonic

P is the total RF power flow in the slow-wave structure

E_z is the longitudinal electric field strength at the surface of the slow-wave structure for the n^{th} space harmonic.

Hence, the interaction impedance is a measure of the longitudinal electric field strength in the interaction region of the CFA. It is assumed that the field decays exponentially away from the surface of the slow-wave structure towards the sole.

Figure 2 shows the RF gain as a function of RF input power level with the interaction impedance as a parameter. The priming current is held fixed at 600 μ A during each of the computer runs. The tube efficiency, η , is marked along the gain curves. These results indicate that even with a priming current of 600 μ A and an interaction impedance of 60 ohms the CFA still requires RF drive levels of 400 watts and greater to achieve useful gain and efficiency.

The gain as a function of priming current for an input RF level of 900 watts and two values of interaction impedance, $K = 60$ ohms, and $K = 30$ ohms, is shown in Fig. 3. For the case of an interaction impedance of 60 ohms the gain

TABLE I

Assummed Parameters for Theoretical Studies

CFA Parameters

Anode-Cathode Voltage	10 kV
Anode-Cathode Spacing	0.4 cm
Magnetic Field (Uniform)	1050 Gauss
Sole Width	2.29 cm or 1.52 cm
Line Length	19.0 cm
Frequency	2.8 GHz
Interaction Impedance	Variable
Attenuation	.14 db/Wavelength
Phase Velocity	2.4×10^7 m/s
Priming Current	Variable
RF Input Power	Variable

Secondary Emission Parameters

δ_{max}	4 at 500 V
1st crossover	25 V
2nd crossover	2000 V

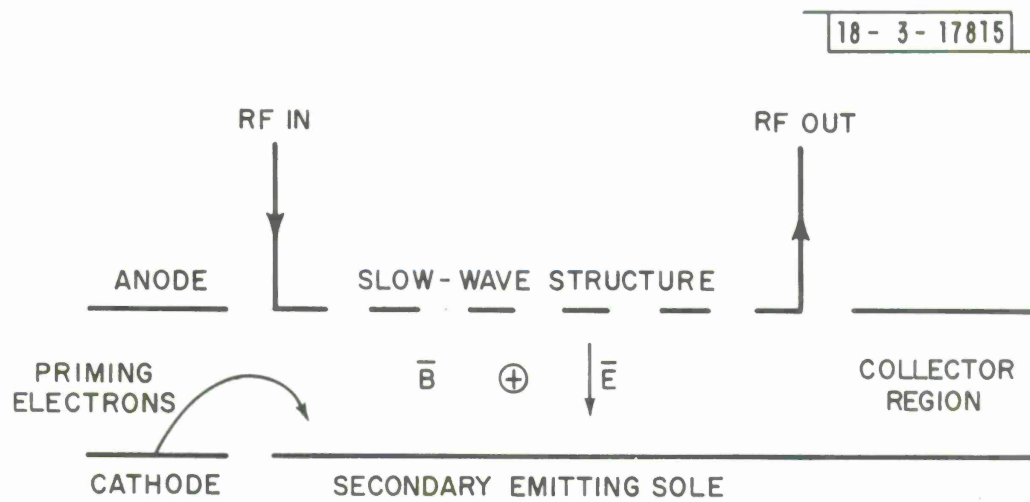


Fig. 1. Linear RF-keyed crossed-field amplifier with secondary-emitting sole and a source of priming electrons.

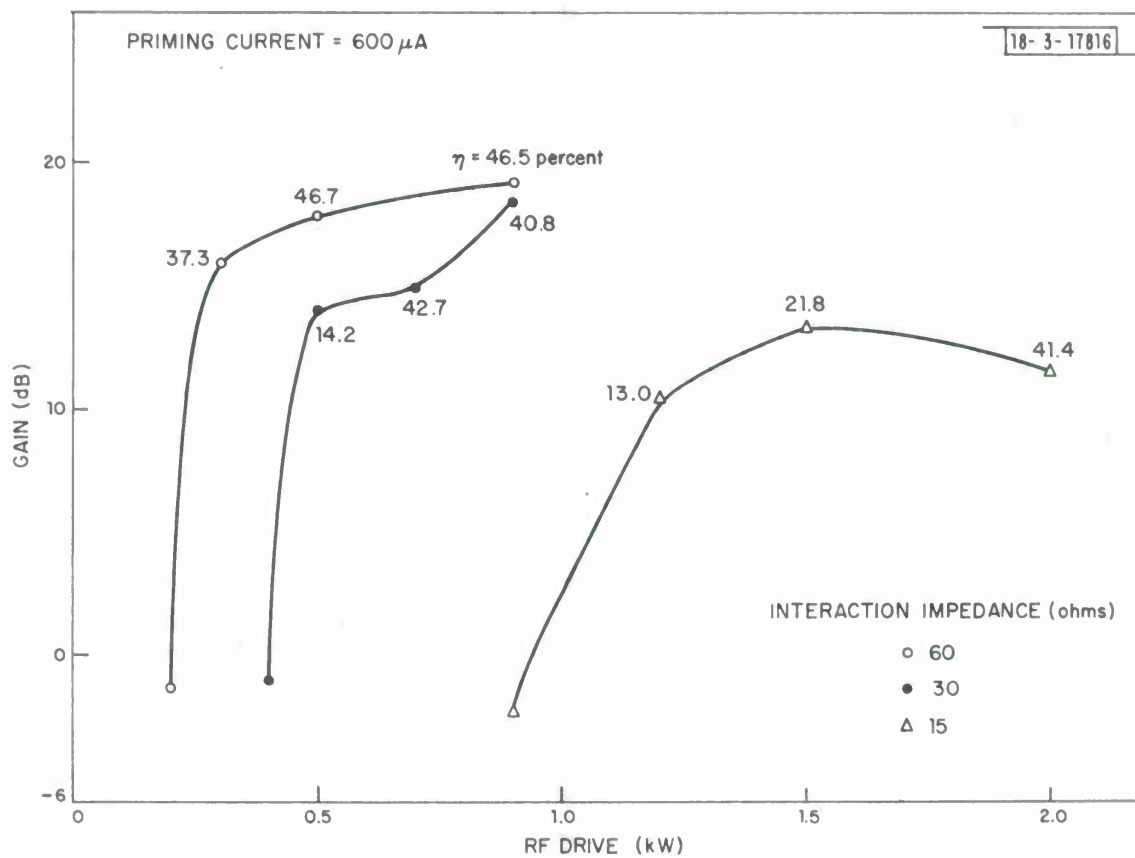


Fig. 2. Gain as a function of RF input drive for three values of interaction impedance, $K = 60\ \Omega$, $30\ \Omega$, $15\ \Omega$, respectively. The efficiency, η , is marked along the gain curves.

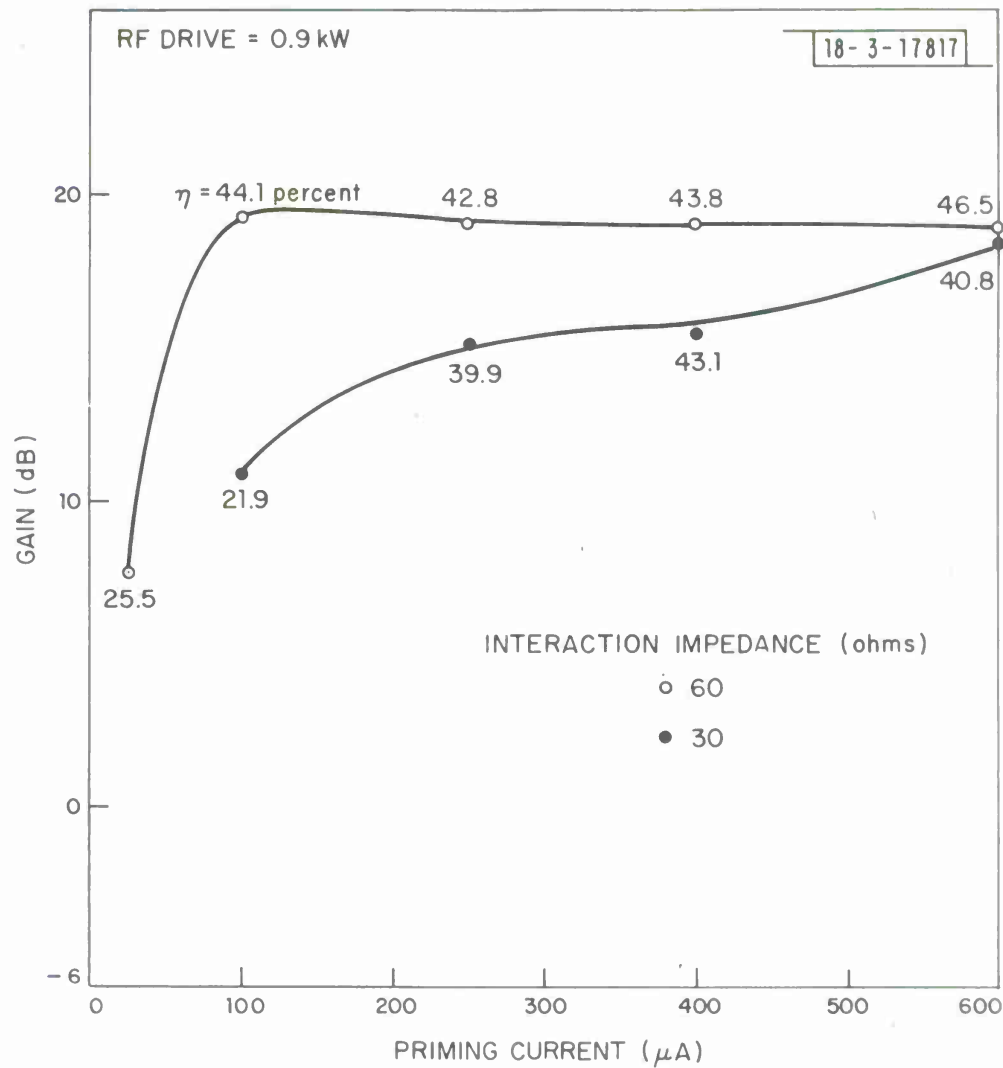


Fig. 3. Gain as a function of priming current for two values of interaction impedance, $K = 60 \Omega$ and $K = 30 \Omega$, respectively.

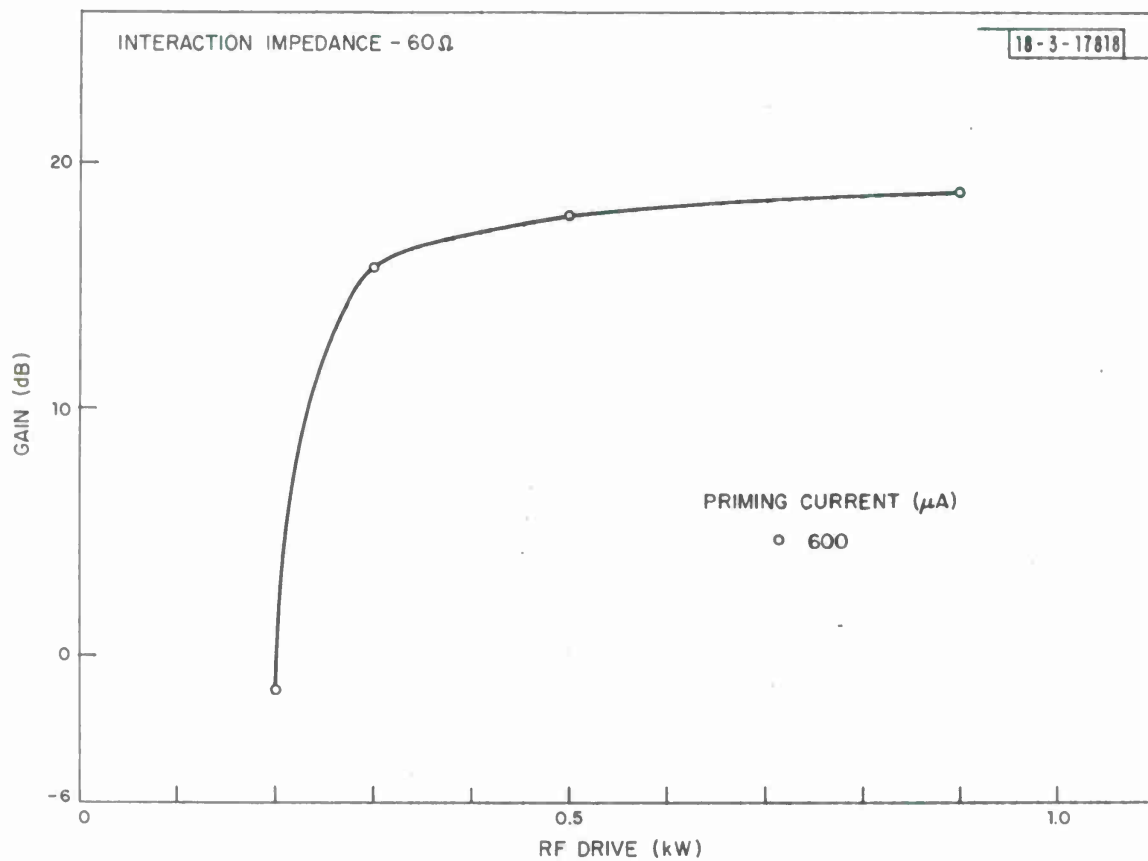


Fig. 4. Gain as a function of RF input drive for three values of priming current, $I = 600\mu\text{A}$, $I = 250\mu\text{A}$, $I = 100\mu\text{A}$, respectively.

is relatively independent of the priming current for values from $100\mu\text{A}$ to $600\mu\text{A}$. However, even a priming current of $100\mu\text{A}$ is still higher than values which can be obtained by "natural" field emission and hence a CFA of the above design will require either a thermionic source, or a tungsten-fiber field emitter, to produce these levels of current. Figure 4 shows the gain as a function of RF drive for three values of priming current with the interaction impedance 60 ohms. Above a level of 500 watts the gain is essentially independent of priming current.

The above results show that to build an RF-keyed CFA using an anode-cathode voltage of 10kV requires that the printed-circuit slow-wave structure have an interaction impedance between 30-60 ohms and a priming current of between 200-600 μA , to give reasonable gain and efficiency for RF drive levels of 500 watts and above. Note that since the gain of the tube in this case is on the order of 18db the output power levels will be 30 kW and above. It is doubtful that the printed-circuit slow-wave structures can handle peak power of the above level.

III. Experimental System

The physical parameters of the printed-circuit meander-line slow-wave structure used in the experimental tube are shown in Fig. 5. A gold meander-line is deposited on one side of a beryllia substrate and a similar metal ground plane on the opposite side. The phase velocity and the interaction impedance of the structure were measured by forming a cavity 10 unit cells long, where a unit cell is defined in Fig. 5. By measuring the frequency of

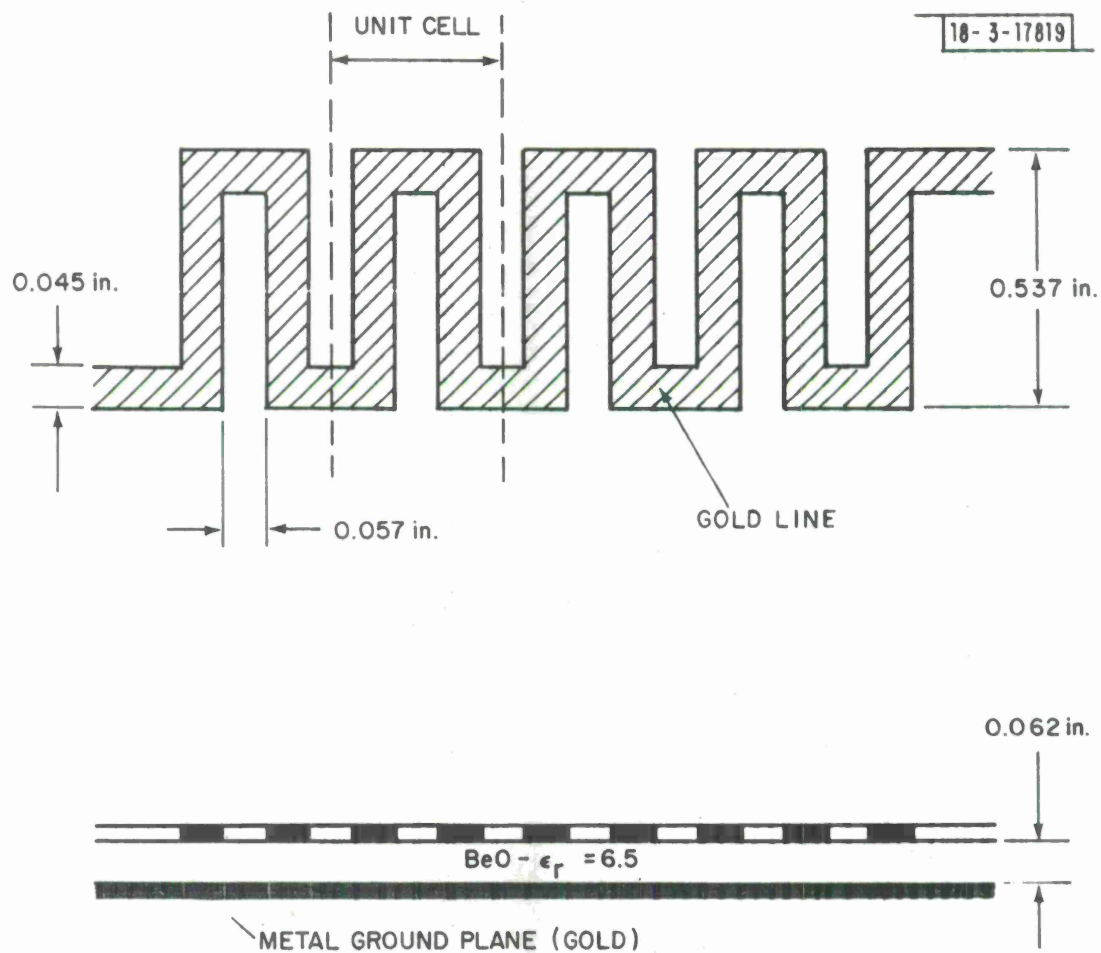


Fig. 5. Physical parameters of the slow-wave circuit meander-line and beryllia substrate.

the resonant modes and detecting the number of wavelengths corresponding to each mode a curve of phase shift per unit cell versus frequency can be plotted. The phase velocity is then given by

$$v_p = \frac{\omega p}{\phi} \quad (2)$$

where ω is the resonant mode circular frequency, p is the length of the unit cell, and ϕ is the phase shift per unit cell. The measurements are shown in Fig. 6 where the solid line is a theoretical curve generated by Weiss (Ref 5).

The interaction impedance was measured by perturbing the above cavity using a sheet of Mylar, 0.008 inch thick, which covered the meander-line circuit. The interaction impedance is given by, (Ref 6),

$$K = \frac{L}{\Delta V} \frac{1}{\epsilon_o (\epsilon_r - 1)} \frac{4s}{p} \frac{M^2}{\beta^2 v_g} \frac{\Delta f}{f_o} \quad (3)$$

where L is the length of the cavity

ΔV is the volume of the dielectric perturber

ϵ_o the permittivity of free space

ϵ_r the relative permittivity of the perturber

s is the spacing between fingers in the meander line

p the unit cell width of the meander line

β the phase constant

v_g the group velocity

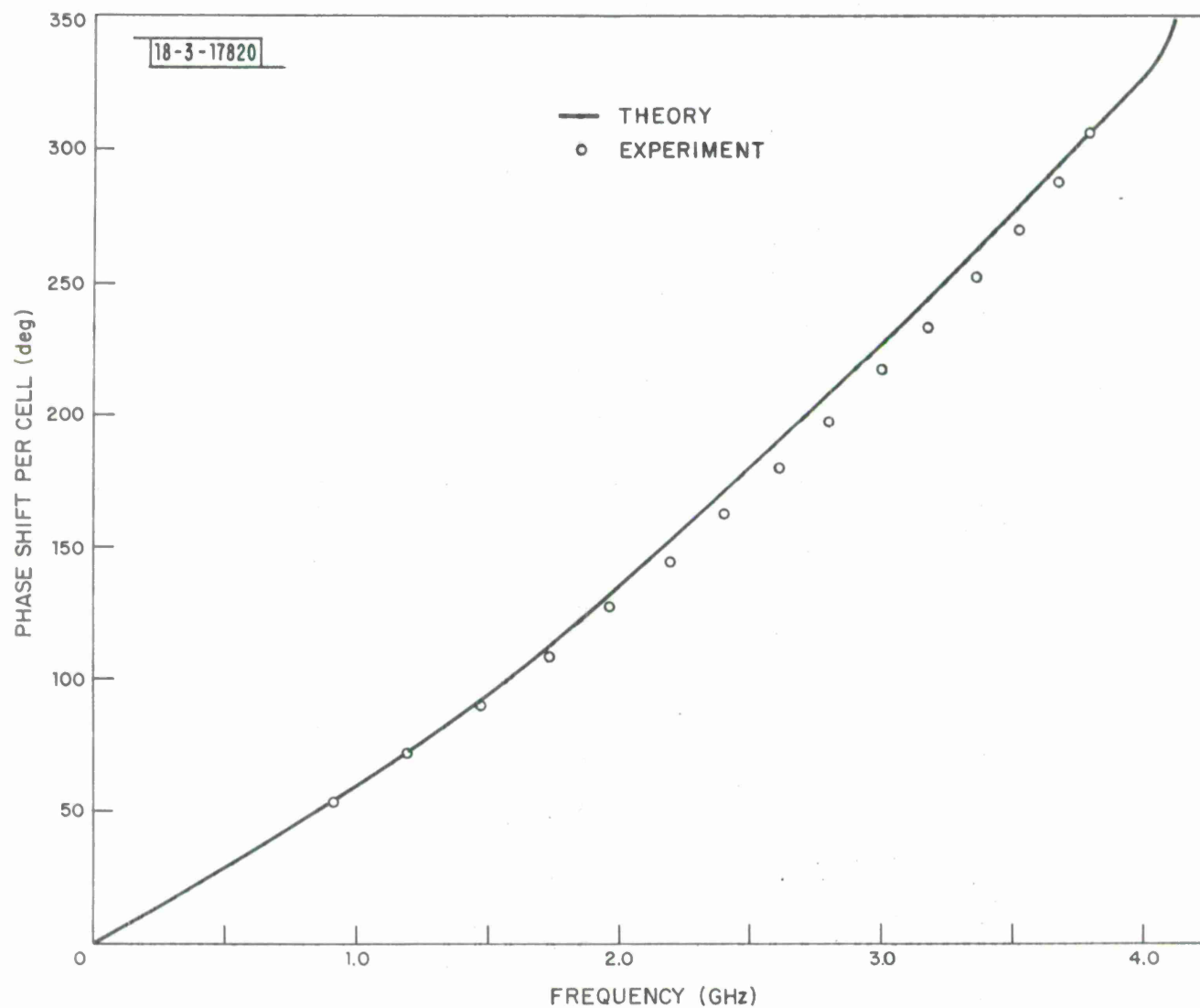


Fig. 6. Theoretical and experimental values of the phase per unit cell, ϕ , as a function of frequency.

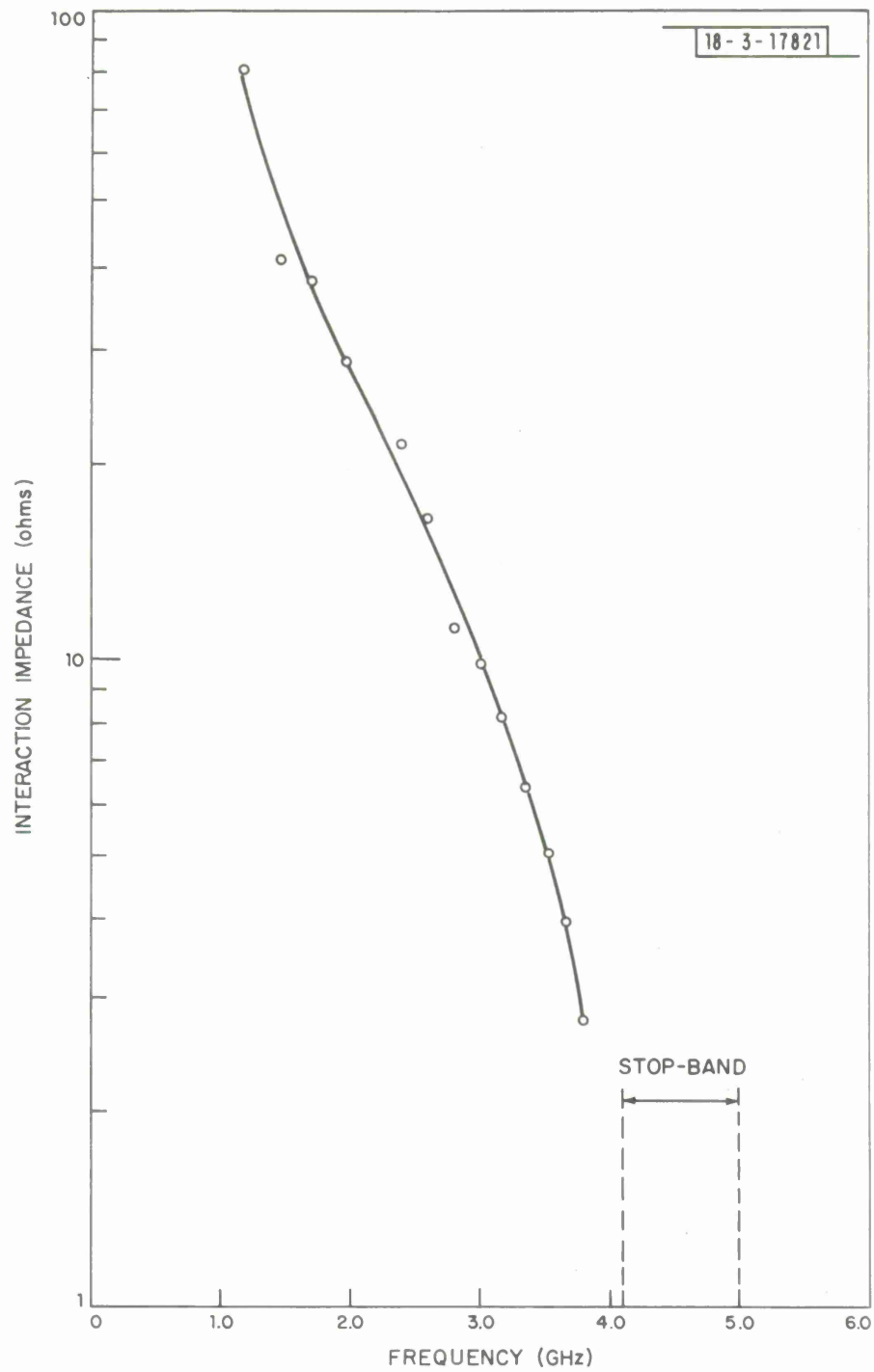


Fig. 7. Experimental values of the interaction impedance of the printed-circuit slow-wave structure as a function of frequency.

Δf the shift of the resonant modes from their unperturbed values
 f_0 the frequency of the unperturbed resonant modes
 and

$$M = \frac{\sin\left(\frac{\phi g}{P}\right)}{\left(\frac{\phi g}{P}\right)} \quad (4)$$

where ϕ is the phase shift per cell. The results are shown in Fig. 7, where the interaction impedance is plotted as a function of frequency. For the design frequency of the CFA the interaction impedance of this structure is 11 ohms.

The secondary-emitting sole material was a gold magnesium oxide cermet, (Ref 9) with a cross-over voltage of 25 V and a peak yield of 4 at 500 V.

Figure 8 shows the RF output pulse and modulator current pulse when a tube constructed with the above slow-wave structure and secondary-emitting sole was operated. The input power level is 1.2 kW and the gain is 2.5 db. For input power levels slightly above the 1.2 kW level RF breakdown occurred and severe sustained oscillations were detected on the modulator current output. When the structure was dismantled sputtering of the gold at the output end of the slow-wave structure was observed. The priming current was 600 μ A. The experimental value of 2.5 db gain at RF input levels of 1.2 kW with an interaction impedance of 11 ohms is in reasonable agreement with a theoretical value of 1.0 kW for an interaction impedance of 15 ohms, as seen in Fig. 2. Since the RF level is inversely proportional to the interaction impedance the theoretical value of RF input power level at 11 ohms is 1.45 kW.

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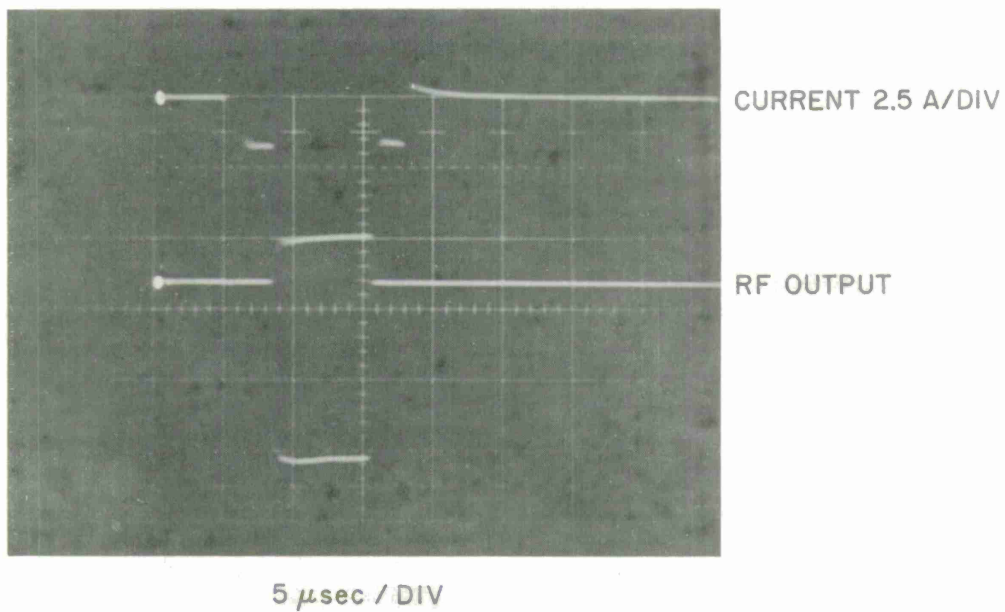


Fig. 8. Photograph of the total modulator output current and RF output pulse at a frequency of 2.8 GHz.

IV. Conclusions

The preceding results indicate that to build an RF-keyed CFA using printed-circuit techniques and keying at an input level of 100 watts and an output of the order of 6 kW would require a new secondary-emitting material with a cross-over voltage of between 10-12 volts. This is based on the belief that it is unlikely that a printed-circuit meander-line can be constructed with an interaction impedance of 240 ohms at S-band frequencies. Although the printed-circuit structure used in the present program had a very low interaction impedance it may be possible to design a structure with an interaction impedance of between 30-60 ohms in S-band. Hence, to reduce the RF-keying level from the 500 watts shown in Figure 2 to the 100 watt region requires a reduction of the secondary-emitting cross-over voltage from 25 volts to approximately 10 volts. At present there are no known materials suitable as a secondary-emitting sole with such a low cross-over voltage. Using existing secondary emitters with a higher interaction impedance slow-wave structure offers the possibility of building an efficient RF-keyed tube which keys above 500 watts. However, the output power level in this case is likely to be higher than the capability of printed-circuit structures. Also, at such high-power levels the lifetime of the gold magnesium oxide secondary-emitting sole is unknown and may be limited. No high-power lifetime of this material has been carried out.

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